CALCULATED AND OBSERVED CHANGES IN SEA SURFACE TEMPERATURE ASSOCIATED WITH HURRICANE PASSAGE

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THESIS

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Associated with Hurricane Passage

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ABSTRACT

Analyses were made of the sea surface temperatures in the Gulf of Mexico in August for the four years 1965 through 1968. No one pattern was found to predominate. The subsurface temperature profiles were then considered, and a rate of simulated withdrawal of 4000 calories of heat per day was made, until there was no heat in excess of 26°C. This withdrawal represented heat removed during passage of a hurricane. Difference analyses were constructed for the initial sea surface temperature at each station and that after twenty-four hours of simulated withdrawal. The differences ranged from less than one degree to over four degrees. Again, no consistent pattern was found but generally areas of high concentrations of heat experienced smaller decreases. Actual sea surface temperatures collected after two hurricanes were then analyzed and compared to temperature patterns predicted by the computer model. Illustrations of the relative availability of sensible heat energy for different sea surface temperatures are presented and a hypothesis made to account for the greater than average intensities of Hurricanes Betsy (1965) and Camille (1969).

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I. INTRODUCTION

A. REVIEW OF THE LITERATURE

The tropical cyclone, or hurricane, is one of the most destructive of all natural phenomena. Early man feared these storms and because he could not flee, sought shelter. As the years have passed, man's curiosity has tempered his fear and has brought him back to observe this phenomena. His reason has led him to some degree of understanding of it and has, more recently, led him to consider controlling or re-directing this behemoth of destruction.

Within the last quarter-century much has been learned about conditions required before a hurricane can develop. Palmen [1948] determined the need for sea surface temperatures in excess of 26°C. Riehl [1954] found that in addition to warm water a pre-existing low level tropical disturbance, customarily an easterly wave, and divergence at high levels were requisite to formation. Riehl also described the basic mechanism of the hurricane and the dependence of this mechanism on the introduction of latent and sensible heat to the storm from the water beneath. Malkus [1962] summarized what was then known about hurricanes and large scale interactions in general. She referred to a hurricane as a giant thermal engine where the latent heat of condensation is the primary source of energy. She states that to sustain the pressure gradients, "two coupled processes are necessary: first, a greatly magnified oceanic input of sensible and latent heat, and secondly, the undilute release of the latter in concentrated hot tower ascent, so that air of high heat content is pumped rapidly into the upper troposphere".

The warm core of the hurricane is responsible for its very low central pressure and the associated increase in surface pressure gradient leads to a more intense storm. A cooler core would result in a less intense storm. Dunn and Miller [1964], in describing the dynamics of a hurricane, say that as the entrained air rushes toward the vortex of the cyclonic circulation, the decrease in pressure should lead to condensation, but the latent heat of condensation which is released is not sufficient to maintain the temperatures in the warm core. Thus a hurricane must also receive sensible heat from the sea surface and the more sensible heat received, the warmer the core, the less the central pressure, and the more intense the storm. Conversely, the less sensible heat received from the sea surface, the weaker the storm. Hence, removal of the sensible heat source, such as occurs during passage of the hurricane over cold water, or land, will weaken the storm.

In the more extreme case when hurricanes pass over land the central pressure increases, or they "fill", about twice as fast as the increase in friction alone would indicate that they should. This may be true even though rainfall doesn't diminish (and may even increase due to orographic lifting). So even though the latent heat is still present to maintain the energy of the storm, the addition of sensible heat is not, and the core cools, thus decreasing the intensity of the storm.

Ooyama [1969, after Östlund] notes that tritium measurements indicated that 60-80% of the water in the eye wall of Hurricane Betsy (1965) could have just evaporated from the ocean and he thereby concludes that a tropical cyclone consumes a great deal more latent heat than it can collect from the pre-existing atmospheric vapor.

Thus the hurricane derives much of its energy from the sea beneath it. Temperatures of the surface of the sea over which a hurricane will pass, can then be utilized as an indication of the energy available to the hurricane and hence the relative intensity to be expected of it.

Several independent investigators have pursued the relationship between sea surface temperature and hurricane intensities with qualitatively similar results. Perlroth [1962, 1967] found that hurricanes seemed to intensify over warmer water and fill over cooler water. He also said that knowledge of the near surface sea temperature alone was not sufficient. Rather, it appeared that the vertical sea temperature profile was "an essential criterion for the determination of the occurring energy transfers". Dunn and Miller [1964] also found that abnormally high ocean temperatures probably contribute to a hurricane's intensification.

Recent attempts to simulate hurricanes through use of mathematical models, such as Ooyama's [1969], also demonstrate the probable dependence of intensity of hurricanes upon high sea surface temperatures. But as Gentry [1969] notes, "they parameterize in a relatively simple fashion the effect of air-sea interaction and the transfer of energy by cumulus convection". When more is known about the internal dynamics of the hurricane and the sea beneath, it will be possible to describe their interaction more completely.

B. OBJECTIVE

The objective of this thesis is to determine the rate at which a typical hurricane will change the temperature of the sea surface over which it passes. And to demonstrate how this decrease in sea surface

temperature experienced during passage of the hurricane has affected the energy input to the hurricane.

II. THE APPROACH TO THE PROBLEM

A. GENERAL

Prior to 1965, investigators attempting to study the interaction between the ocean and atmosphere were severely hampered by a lack of an adequate amount of data. Recognizing this need for more data, Dr. D. F. Leipper of Texas A & M University, organized a series of cruises by the University's research vessel, the R/V Alaminos, to collect data from the Gulf of Mexico. Among the cruises, was one in August of each of the years 1965 through 1969. Bathythermographs (BT's) were taken over much of the Gulf during each cruise and these BT's provided the badly needed three-dimensional insight into conditions existing in the Gulf in each of the four years just prior to the hurricane season. These data provided a means whereby the sea surface temperature patterns could be considered in relation to the subsurface thermal profiles as Perlroth [1967] had suggested and a comparison of conditions existing in the four different years could be made.

Previous work by Volgenau [1970] had determined the amount of heat in excess of 26°C available in the Gulf for each cruise and work by Malkus [1962], Leipper [1967], and Whitaker [1967] gave the approximate amount of heat (4000 calories per day) that a "typical" hurricane might be expected to remove from the sea during its transit time over any given column of water with one square centimeter cross-section (square centimeter column).

Two observed BT profiles, each having a sea surface temperature of 29.4°C, are compared in figure (1). The amount of heat in excess of 26°C contained within both square centimeter columns of water is

directly proportional to the shaded area of the profiles. If 4000 calories were removed from each profile as each column was cooled at the surface and mixed convectively, even though the initial sea surface temperatures were the same the resultant temperatures would be significantly different. The surface layers would be isothermal due to the convective mixing which results from the surface cooling. The area to the right of the dotted line in each case represents 4000 calories. The profile containing little total heat would experience a large drop (2.5^{o}C) in sea surface temperature from the loss of this amount of heat, while the profile containing more heat would experience only a small change (0.9^{o}C) in sea surface temperature from the same heat loss. If 4000 calories represented the average amount removed from a square centimeter column by a typical hurricane taking twenty-four hours to completely pass over the column, then one-half of the twenty-four hour total, 2000 calories, would represent the amount removed in a twelve hour transit. One-half of this, 1000 calories, would be that amount removed in a six hour transit, and so forth.

A computer model was developed which simulated the withdrawal of the heat from a given initial profile, by artificially lowering the sea surface temperature in small increments (0.1^{o}C). The model then calculated, using the simple heat content formula described below, the quantity of heat which was contained within each trapezoidal area produced between the old and new sea temperatures. A cumulative total was kept of the areas of heat artificially removed and when the total reached 1000 calories the sea temperature simulated the passage of a hurricane with a traverse time of six hours. When the total reached 2000, a traverse time of twelve hours was simulated, and so forth. Since the approximate number of calories withdrawn per square centimeter column

of water per day by a typical hurricane is known and the quantity of heat artificially removed is directly proportional to the traverse time, any hurricane traverse time can be represented by a different sea surface temperature and a plot of the BT's for a given cruise and a given traverse time gives some indication of the change in sea surface temperature which has occurred from pre-hurricane conditions. The change of relative input of energy into the hurricane can be estimated from this.

The validity of the system was checked against data obtained by Leipper following Hurricane Betsy (1965). A comparison of this observed data with the results of the computer model was made within the general area traversed by the hurricane winds.

In addition to the Alaminos cruises, an attempt was made to gather data which indicated conditions in the Gulf of Mexico just prior to, and subsequent to, Hurricane Camille (1969). Similar handling of the available data, plus some qualitative reasoning, then served to indicate possible origins of Camille's destructiveness.

B. THE MODEL

A computer model was developed based on previous determinations of heat transferred from the sea to the air during passage of a hurricane. For this determination, it was assumed that an average hurricane would remove approximately 4000 calories from the column of water beneath each square centimeter of sea surface traversed per day. This amount was an average approximation based on the results of Malkus [1962], Leipper [1967], and Whitaker [1967]. With the passage of a hurricane over a given area of water, the winds (and resultant transfer rate of heat according to the transfer formulas below) increase to a maximum,

then decrease. The use of the 4000 calorie amount, therefore, assumes that a specific square centimeter column of ocean undergoes a continual change of influence during a specific time period, and the average transfer, then, is a result of the total influence, and not of any one specific level of wind speed.

Certain assumptions have been used in the construction of this computer model. The bathythermographic traces used were composed of linear segments between the surface and the five meter depth and for every subsequent five meter interval. This is a standard Naval Oceanographic Data Center format. Each trace was assumed to remain constant until subsequent influence by the hurricane would cause restructuring of the trace. Because the curvature of a profile is slight in most intervals the linearity assumption did not radically alter the overall temperature structure, and any error which resulted from this assumption did not materially change the end results.

Internal waves, which might have caused a substantial change in layer depth are not observable on a single BT trace and were therefore neglected. The presence of an internal wave at the time of the BT observation could substantially affect the subsequent restructuring of the temperature profile at the station. However, by using a large number of stations, an overall pattern of unaffected profiles in the mean is established.

It was further assumed that no inversions existed in the temperature profile of any station. Although Stevenson and Armstrong [1965], in their study of Hurricane Carla (1961), noted that inversions can lead to very large reductions of sea surface temperatures with passage of a hurricane, their conclusions resulted from data obtained in

shallow coastal water where inversions are common and pronounced due to the fresh water run-off lying on top of the more saline sea water. Away from the coast the brackish water becomes mixed with the saline and the inversions are weaker and far less frequent. Very few of Leipper's profiles contained inversions, and those noted were typically weak and shallow. In reality, as heat is withdrawn from these brackish layers they will eventually become denser than the subsurface layers, and they will subside and mix with the saltier, warmer water below. Without knowledge of the specific temperatures, and salinities involved, however, and without a much more complicated computer program, it would be impossible to determine the exact temperature at which this mixing would occur for each individual inversion. The heat contained in any inversion was therefore artificially redistributed to the surface layers to produce an equivalent profile without inversions and the magnitude of total heat contained was not thereby materially influenced. This assumption avoided complicating the program to handle accurately a small number of stations.

The simple heat content formula,

$$Q = \overline{\rho\, c_p\, \Delta T\, h}$$

where

ρ = density, taken as $1\ \frac{gm}{cm^3}$

c_p = specific heat of sea water, taken as $1\ \frac{cal}{gm}$

ΔT = temperature increment

h = average depth of incremental layer in cm

was used to calculate the heat available in excess of 26°C. As the surface layer was cooled, it subsided and mixed convectively with the layers beneath until a sea surface temperature of 26°C was reached.

Transfer of heat from the ocean to the atmosphere is essentially non-existent below this sea surface temperature, as found by Palmen [1948], and Kotsch [1957, after Kasahara].

The transfer of heat from the ocean to the atmosphere is expressed mathematically through use of the standard flux transfer equations as given by Malkus [1962]. The general form for these equations is:

$$F_s = -\rho K_s \frac{d\bar{s}}{dz}$$

where

f = flux transfer

s = property in question

K = constant for the property

ρ = density

z = vertical distance

The equations used to express the transfer of sensible and latent heat from the ocean to the atmosphere are derived from the general equation and are, respectively:

$$Q_s = \rho c_p c_d (T_0 - T_a) u_a$$

and

$$Q_e = \rho L c_d (q_0 - q_a) u_a$$

where

Q_s, Q_e = rate of transfer of sensible and latent heat, respectively

c_p = specific heat of sea water

c_d = transfer coefficient

L = latent heat of condensation

T = temperature

ρ = density

q = specific humidity

u = wind speed

a - refers to height of observation

0 - refers to ocean surface.

It must be noted that although a "typical" hurricane was assumed to remove approximately 4000 gm-calories per square centimeter per day, this amount is by no means the same for all storms. The transfer formulas are linearly dependent on wind speed, so a more intense hurricane would extract at a rate in excess of this one for a "typical" hurricane. The intensity of the storm may be simulated by varying the total number of calories extracted per day in the model as required.

For a constant wind velocity, the sea-air temperature difference in the sensible heat transfer equation is the key to energy input to a hurricane. If the difference is small, there is little input and conversely, a large difference represents large input. For example, assume that the air temperature is 26°C, then water at 30°C will add twice as much sensible heat energy per unit time as will water at 28°C. Or, to take another view, if the original sea temperature was 30°C and dropped to 28°C during the passage of a hurricane, the sensible heat energy input into the hurricane would be halved. The addition of sensible heat causes a warming of the core, with a resulting increase in the pressure gradient and correspondingly stronger winds. Since wind speed is a linear factor in both transfer equations, this increase in wind speed leads to a subsequent increase in transfer of both sensible and latent heat to the atmosphere.

Conversely a rapid decline in the sea surface temperature during passage of a hurricane results in rapidly decreasing sensible heat energy input to the hurricane, a cooling of the core, and a reduction in the hurricane's intensity. This decrease in wind speed results in reduced sensible and latent heat input as indicated above by the transfer formulas and thereby reduces the intensity even more. The original high sea surface temperatures then, are important to the intensity of the hurricane but so, also, is the ability of the sea to maintain those temperatures for as long as it takes the hurricane to pass.

The model was restricted to provide for removal of heat from a stationary surface layer only. There were no provisions made to consider any advection of heat due to ocean currents. This assumption also applied to surface advection due to wind stress. Any currents which traverse an area of consideration after a hurricane and before collection of post-storm verification data would have to be applied subjectively to the computer model results, with the magnitude of advection (and subsequent mixing) directly proportional to the delay in verification of the results.

Additionally, the total number of calories removed from a column of water with surface area equal to one square centimeter per day is an average value for the entire area over which hurricane force winds pass. As a result of the motion of the hurricane the actual amount removed from a square centimeter column to the right of the track of the eye of the hurricane should be greater than the average value for the whole storm, and that removed from a square centimeter column to the left of the track of the eye should be less than the average value.

To account for this difference it would be necessary to run the program twice, using different values of the total number of calories removed, so that each value is a representative average of the amount removed from beneath each half of the storm. (This could be further refined to include the variation in actual mean wind speed within the hemisphere being considered.) The results of the right hemisphere model should then represent those sea surface temperatures to the right of the track of the hurricane eye and vice versa for the left. The two sides might then be combined to represent the entire track. However, this refinement was not used here.

In addition to the aforementioned assumptions, this model assumed that the up-welling discussed by Leipper [1967] did not reach the surface during the time intervals studied. The longer it takes a hurricane to traverse a given area, the greater is the likelihood that up-welling will occur. When this happens validity of this assumption is abruptly terminated. In the two actual hurricanes studied, no up-welled water was observed at the surface. The change in sea surface temperature, therefore, was due only to the removal of heat from the surface layer by the hurricane.

The net result of the above assumptions was that this model considered essentially a stationary area of warm ocean with a temperature profile containing no inversions being passed over by a typical hurricane. For the observed initial conditions the model then constructed sea surface temperatures which would have resulted for different hurricane propagation speeds across each station based upon an average number of calories extracted per day by the storm.

III. DISCUSSION OF RESULTS

A. SEA SURFACE TEMPERATURE

The sea surface temperature in August of 1965, was characterized by a broad band of warm water oriented from Cuba to Louisiana with another warm tongue extending to the southwest at approximately mid-Gulf. This pattern is shown in figure (2). The maximum sea surface temperatures were 30-31°C, and were found over much of the warm band mentioned above. The coolest water was a very small area to the east of the Mississippi delta where temperatures were less than 28°C. The distributions of data upon which this and the following figures are based are included by Volgenau [1970].

The analysis for 1966, figure (3), showed a distinctly different pattern from that of 1965. Instead of having a long warm tongue extending northward, the Gulf was warm only to the north of Cuba and the areas over 30°C were all small. The north-central Gulf was significantly cooler, but again, the warmest water in the Gulf was 30-31°C. The large cool area north of Yucatan was the single most noteworthy feature.

The highest surface temperatures of the four years analyzed were observed in 1967, figure (4). This analysis contains a small area of 31-32°C water and significantly large areas of 30-31°C water. The sea surface temperatures were much higher than in 1966 but the warmest waters also covered a broader area than they did in 1965.

In contrast to the generally high temperatures of 1965 and 1967, those of 1968, figure (5), were somewhat lower. The warmest water was to the north, as it was in 1967, but it was not as warm. This analysis

shows large areas of relatively cool surface water of 28-29°C temperatures in the same areas that warmer waters were located in 1965 and 1967.

The climatological sea surface temperatures, as obtained from the USNOO Atlas [1967] indicate that maximum values found in this area of the Gulf for this time of year are 30-31°C. The minimum sea surface temperatures are 26-28°C and the mean temperatures are approximately 29°C. The temperatures actually observed during the four years studied were, in general, between the climatological mean and maximum values. The significance of these sea surface temperatures lies in the variability of the observations from place to place and year to year. There was no definite pattern found to be associated with the sea surface temperatures during all of the four years analyzed.

B. TOTAL FUEL

The "total fuel" analysis depicts the maximum time that a typical hurricane may take to cross any given area and still have a source of heat in excess of 26°C beneath it upon which to draw. These analyses provide an interesting insight into the true availability of heat to the hurricane, not necessarily indicated by the temperature of the sea surface. Similar analyses were done by Volgenau [1970], who expressed the heat in calories per square centimeter of ocean surface. The heat in the analyses included herein is expressed in days. Thus a point on the 3 contour would indicate that a hurricane could take three days to cross that spot before the sea surface temperature would be reduced to 26°C and the transfer of heat from ocean to air would essentially cease, assuming that cold up-welled water had not yet appeared at the sea surface.

In 1965, the maximum concentration of heat was located midway between Cuba and Louisiana, figure (6), virtually beneath the area of maximum sea surface temperatures. A hurricane could take up to five days to cross this region before it would exhaust the excess heat above 26°C. A small area of relatively cool water was located just north of Cuba which would support a crossing for only one or two days.

The 1966 analysis, figure (7), depicts a pattern somewhat similar to that of 1965, but the warmest waters were farther to the north and west. In addition, they were capable of supporting a hurricane during a six day crossing. It is especially interesting to note, that the increased total heat content was not necessarily associated with warmer surface water. In fact, just the opposite is true in this case. Much of the area of water with greatest total heat content, lay beneath relatively low temperatures at the sea surface.

The 1967 analysis, figure (8), showed a very low total fuel content in general, much less than either 1965 or 1966. The warmest water lay in approximately the same location as in the previous years but the areas capable of support for five days or more were small and isolated. An important incursion of relatively cool water appeared to the northeast of the warm core. This cool water was especially significant since it lay directly beneath the highest sea surface temperatures recorded in the four year period of consideration, a situation just the reverse of that found in the previous year.

The warm core which had been present during the previous three years, shifted to the northeast in 1968, figure (9), and occupied much of the area dominated by cool water in 1967. In one area, this core could have sustained a hurricane passing overhead for six to seven

days, the longest time of any station analyzed. The typically warm area to the southwest contained much cooler water this year and could not have sustained a hurricane for even one full day.

In summary, an area of warm water was found near the western tip of Cuba in each of the four years. This was not unexpected due to the inflow of warm tropical water between Cuba and Yucatan. The central Gulf region, however, was not as consistent. While a warm core typically appeared, oriented generally in a northwest-southeast direction between Louisiana and Cuba, its location was not consistent, nor was its magnitude. Areas of cool water appeared in various locations on either side of the warm core. No correlation was possible between these areas of extremes, either warm or cold, and their associated sea surface temperatures. In fact, areas of highest total heat were on occasion found beneath relatively low surface temperatures and vice versa.

C. SEA SURFACE TEMPERATURE DECREASE WITH PASSAGE OF A HURRICANE

The previous sections demonstrate that in order to determine how a typical hurricane will affect the sea surface temperature, it is necessary to consider the initial thermal structure of the entire water column. Thus the computer model described above was used to simulate the effects of passage of a typical hurricane over the initially observed waters of the Gulf of Mexico during each of the four years, 1965 through 1969. The model gave cumulative results of the change in sea surface temperature from the initial pre-hurricane temperature, based on intervals of six hours. For example, for each given location, the model considered hurricane passage times of 6, 12, 18,... hours until the entire amount of heat in excess of 26°C had been

removed. A twenty-four hour sea surface temperature change analysis would approximate a storm with a 200 nautical mile diameter of hurricane force winds and moving at about 8 knots. This analysis was considered to be representative of the overall effect of a hurricane on the sea surface temperatures.

The change in sea surface temperatures after twenty-four hours associated with the 1965 temperature pattern is shown in figure (10). In general, the change for 1965 was 1-1.5°C for the deeper portions of the Gulf. The cool tongue shown to the west of the warm core in the total heat analysis, figure (6), also appeared as an area of greater change in sea surface temperature. It was also expected that shallow coastal areas would experience a large change due to their typically shallow mixed layer depth and this expectation was realized.

The 1966 analysis, figure (11), was considerably more complicated and approximated the general pattern of the corresponding total fuel analysis, figure (7). Most of the Gulf was represented by twenty-four hour temperature reductions of 1-2°C. The relatively large area which represented temperature reductions of one degree or less was the same area which contained the greatest total fuel.

In the 1967 analysis, figure (12), the areas of maximum change of the sea surface temperature were associated with that area of the Gulf which contained the smallest amount of total heat. The amount of change in some areas was greater in 1967 than either of the previous two analyses. There was a broad band of reductions of sea surface temperatures of over two degrees and in two areas, reductions of over three degrees were noted and one small area had a reduction of four degrees. In general, these large reductions occurred under the

warmest initial sea surface temperatures this year because there was no large reserve of heat beneath them. There were no areas of reductions of less than $1^{o}C$.

The greatest reductions in 1968 sea surface temperatures after twenty-four hours, figure (13), were not as large as 1967 but were larger than either 1965 or 1966. While most of the Gulf experienced reductions of $1-2^{o}C$, there were sizable areas of reductions in excess of $2^{o}C$ and one station lost over $3^{o}C$. There were also significant areas where reductions of less than $1^{o}C$ occurred.

In summary, the changes in sea surface temperatures associated with the passage of a hurricane were found to vary substantially from one year to another during the four years studied. The smallest reductions were generally associated with the areas of greatest total heat content and the largest reductions were frequently found to be associated with the areas of smallest total heat content. Furthermore, there was little association noted between the initial sea surface temperature and the magnitude of the subsequent reduction of sea surface temperature due to the passage of a hurricane. Areas of larger than average reductions were found beneath both surface waters that had initially been either warmer or cooler than average.

IV. COMPARISONS OF PREDICTED AND OBSERVED SEA SURFACE TEMPERATURES FOLLOWING HURRICANE PASSAGE

A. HURRICANE BETSY (1965)

The two worst hurricanes of the past decade, in terms of destruction, occurred in 1965 and 1969. Fortunately, research cruises were conducted by Texas A & M University, under the direction of Dr. D. F. Leipper, before and after Betsy in 1965. A limited amount of data from before and after Camille in 1969 was also obtained from several sources. The computer model was applied to these pre-storm data and by using an average diameter and average speed of hurricane movement for each storm resultant post-storm sea surface temperatures were calculated. These patterns were then compared to the post-storm sea surface temperature patterns actually found.

The 1965 pre-Betsy sea surface and total fuel patterns are shown respectively in figures (2) and (6). The hurricane force winds in Betsy had an approximate diameter of 176 miles and the storm moved at an average speed of approximately 14.7 knots, according to Whitaker [1967]. Thus, any given locations traversed by the storm would have been subjected to a total crossing time of twelve hours or less. This would represent a removal of approximately 2000 calories of heat, or less, per square centimeter column by Betsy.

The computer model sea surface temperature pattern which would result from a twelve hour transverse time is shown in figure (14) and the sea surface temperatures actually observed by Leipper subsequent to Betsy are shown in figure (15). The overall pattern in each case is similar in some respects.

The maximum observed temperatures in both analyses were 29-29.5°C and they occurred in the vicinity of 26°N 87°W. To the northwest of this warm tongue, in both cases, was the coolest water. The minimum calculated temperature was 27.5°C, while that actually observed was 26.9°C. This single report was subsequently removed in the subjective smoothing of the analysis. The lowest temperature was found to the right of the track in the area of maximum winds where greater than average cooling could result from the long traverse time and higher than average winds. In both cases, a narrow tongue of cooler water bisected the large warm area which lay parallel to the coast. The bisection occurred south of the Mississippi Delta in the vicinity of 28.5°N 89°W in the predicted analysis and this feature was actually observed slightly to the southwest, near 28°N, 89.5°W. Warmer areas of 28-29°C water were to the northeast and southwest. The cool water extended farther south and east than was predicted by the model, and the warm area Leipper found southeast of the Mississippi Delta was larger than that of the model.

A more accurate fitting of the model sea surface temperature pattern to that actually found results if consideration is given to the overall current pattern in the area at this time, as shown by Leipper [1970]. The clockwise gyre he found in the area could tend to cause a compression of the central warm area and an elongation of the cold tongue toward the east over the time interval between Betsy and Leipper's cruise, thus causing the model's results to eventually more closely approximate Leipper's observations. Assuming this to be the case, the model's results would be more representative of the actual conditions immediately after the passage of the hurricane than

would the pattern observed some days later by Leipper, and some conclusions about relative energy input to the hurricane from the sea may be drawn.

Based on the results of the computer model, it can be seen that Betsy had a rather substantial input of fuel during virtually all of her passage across the central Gulf. Initially the large $30^{\circ}C$ warm tongue, figure (2), provided significantly more input than would have been available during any of the other three of the four years analyzed. Even after passage, most of Betsy's path was cooled only about one degree centigrade.

Assuming that the air temperature within Betsy was $26.0^{\circ}C$, the Malkus transfer formulas above yield a relative sensible heat transfer rate decrease in the warmest area of 25% as determined in the following manner. The warmest water was $30.0^{\circ}C$ and would thus produce a relative input proportional to 30.0 - 26.0 = 4.0. This same surface water cools approximately $1.0^{\circ}C$ during passage of the hurricane so near the end of the influence period the temperature would approach $29.0^{\circ}C$. Then the new relative input would be 29.0 - 26.0 = 3.0. The decrease from 4.0 to $3.0^{\circ}C$ is a reduction of one-fourth or 25 per cent, but the relative input in the warmest area (which covered most of the path) was still 3.0. In 1966 or 1968 the original relative input over the same area for the same air temperature would have been similar in some small areas which had sea surface temperatures in excess of $30.0^{\circ}C$, but with the large areas of cooler water the average initial input would have been closer to 29.0 - 26.0 = 3.0 since most of the path contained sea surface temperatures of approximately $29^{\circ}C$. Thus the input initially would have been 25 per cent less and the subsequent reduction of the

sea surface temperature during passage of the hurricane would have further reduced it. In 1968, for example, this 28°C water would experience about a 0.7°C drop during a twelve hour passage time. Thus the relative input would change from 3 to 2.3 during passage of the hurricane. The average input then would have a relative value of 2.65 vice that of 3.5 for 1965. Thus the average input of sensible heat energy into the 1965 storm compared to that for the same storm crossing waters with the temperature characteristics of the 1968 analyses, figures (5), (9), and (13), is 3.5/2.65 or 132 per cent, an addition of almost a third more sensible heat energy.

B. HURRICANE CAMILLE (1969)

The data available before and after Camille, 16-17 August 1969, is not nearly as abundant since no specific cruises were conducted to investigate the temperature profile in the central Gulf just prior to the storm. There were some observations taken by the USNS Kane shortly after the passage of the hurricane which offer some idea of the post hurricane temperatures, figure (16). From the data recorded at Fleet Numerical Weather Central, Monterey, California, during August, it is possible to gain some insight into the conditions existing in the central Gulf when Camille passed through it. On 7 August, an aircraft dropped an expendable bathythermograph (XBT) at 25° 00'N 87° 30'W. This position was approximately eight miles west of the subsequent track of Camille and the sea surface temperature reported was 30.0°C. The only other XBT received within the area of interest prior to the storm was one taken by a ship on 1 August at 24° 04'N; 88° 18'W, some eighty miles west of Camille's track, which indicated a sea surface temperature of 33.4°C. Although the profiles of the two XBT's are similar, this

temperature, and those of the near surface layers, is unusually high and may be in error. This XBT was therefore neglected.

Data available from Fleet Numerical Weather Central substantiates the existence of large areas of warm surface water in the Gulf prior to Camille in August 1969. Table I indicates the FNWC analysis of sea surface temperatures at representative grid points for 15 August. The FNWC computational programs are such that all reported observations are compared with, and tempered toward, climatological values. Thus an unusually high sea surface temperature could be reduced in the analysis procedure to compare more nearly to its accepted climatological value. The final computed value, although higher than climatology, may still be significantly lower than temperatures actually present at the specific grid position. Thus, actual sea surface temperatures of at least 30.0°C, throughout much of the Gulf would appear to be reasonable.

Camille's hurricane winds extended throughout a fifty mile radius from the center and the storm traveled at an average speed of ten knots according to Hsu [1970]. Thus it would take approximately ten hours to traverse any given point on the track. The sea surface temperature computed by the model was 29.3°C after ten hours. The subsequent data of the Kane indicate that this temperature would appear to be that actually present in the same location following passage of the hurricane. The sensible heat input to Camille then, again assuming an air temperature of 26.0°C, would have had a typical relative value of at least 30.0 - 26.0 = 4.0. Following passage the relative input of sensible heat energy was 29.3 - 26.0 = 3.3, and the average input 3.65. While this is only 4 per cent larger than the average input during Betsy it is 38 per cent greater than it would have been for a hurricane passing over the Gulf in 1968.

TABLE I

FNWC Grid Position	Lat (^{o}N)	Long (^{o}W)	Climatological Sea Surface Temperature	Pre-Camille Analyzed Sea Surface Temperature	Post-Camille Analyzed Sea Surface Temperature	ΔT
I28 J11	24.0	88.5	29.5	30.8	29.3	-1.5
I28 J12	26.5	89.0	29.5	30.5	29.5	-1.0
I28 J13	29.0	89.5	29.2	29.9	29.2	-0.7
I29 J10	21.6	85.5	29.4	29.9	29.5	-0.4
I29 J11	24.2	85.8	29.6	29.4	28.4	-1.0
I29 J12	26.8	86.2	29.4	29.0	27.2	-1.8
I29 J13	29.5	86.5	28.8	28.3	28.0	-0.3
I30 J12	27.0	83.0	29.3	29.7	27.9	-1.8

Comparisons of sea surface temperatures at specific grid points in the Gulf of Mexico.

V. CONCLUSIONS

The sea surface temperature patterns found within the Gulf of Mexico during the hurricane season are neither uniform nor consistent. Furthermore, they are not necessarily representative of the true amount of total energy available to a hurricane traversing these waters because much heat or little heat may lie beneath the surface. A true assessment of the total heat may be made only with the aid of bathythermographic devices.

Because the subsurface heat content may vary significantly from place to place within the Gulf and from year to year, the reduction in sea surface temperature with the passage of a hurricane is neither constant nor predictable based upon sea surface temperatures alone. The entire temperature profile must be considered.

The Gulf of Mexico contained sea surface temperatures approximating climatological maximum values in 1965 and 1969 and these high surface temperatures were supported by sufficiently large quantities of subsurface heat to provide for minimal sea surface temperature reductions during passage of hurricanes Betsy (1965) and Camille (1969). These conditions resulted in a larger than average input of energy to each hurricane and hence endowed each with greater than average destructiveness.

Only through a fairly comprehensive knowledge of the magnitudes of possible energy inputs to a hurricane can a forecaster adequately justify predictions as to the future intensity of the storm. This comprehensive knowledge can only result if the forecaster has access to bathythermographic information for the projected track of the storm.

Accordingly, greater emphasis should be placed on the distribution of airborne expendable bathythermographs (AXBT's) near the expected track of a hurricane. The generalized profile should then be included in hurricane description messages. If possible, AXBT's should also be dropped to the rear of the hurricane from time to time so that some assessment can be made of the amount of heat being removed from the water by that particular storm. The "typical" hurricane values used in this thesis may then be modified to more nearly correspond to the storm under consideration.

Pursuit of this topic should be continued in order to gain more knowledge of conditions within a hurricane. From this knowledge more elaborate mathematical models can then be developed which more accurately depict the inter-relation between a hurricane and its source of power, the sea.

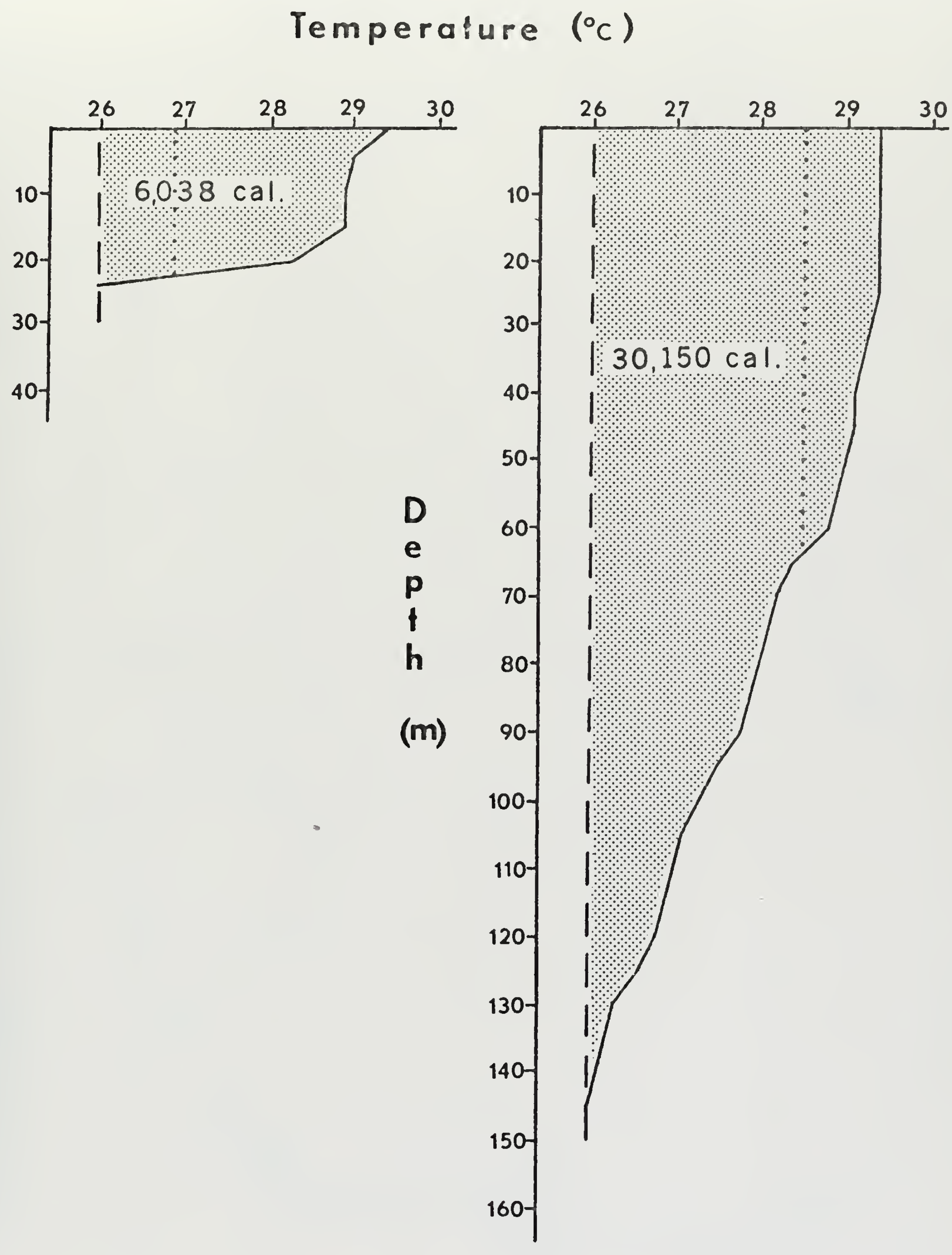
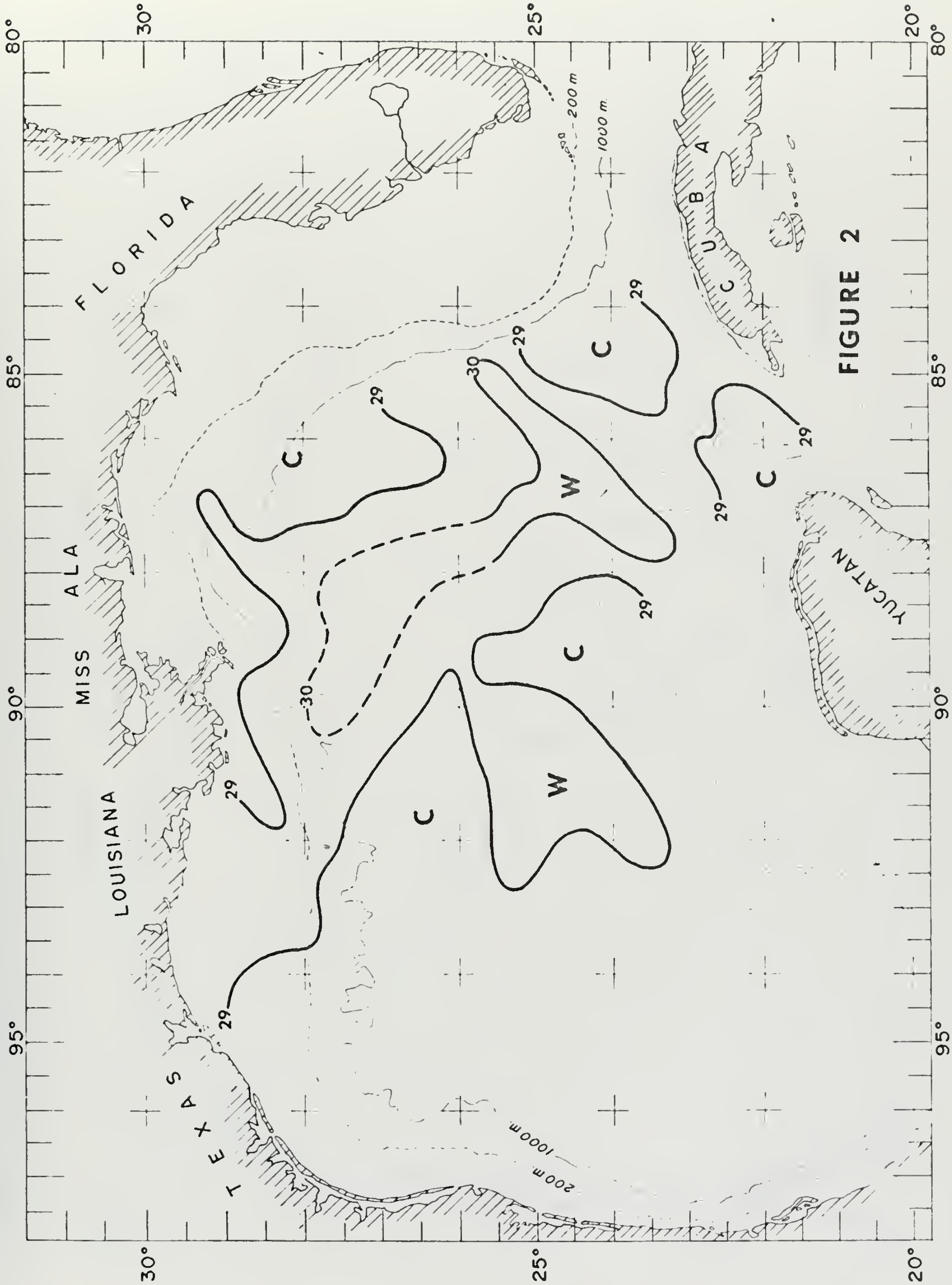
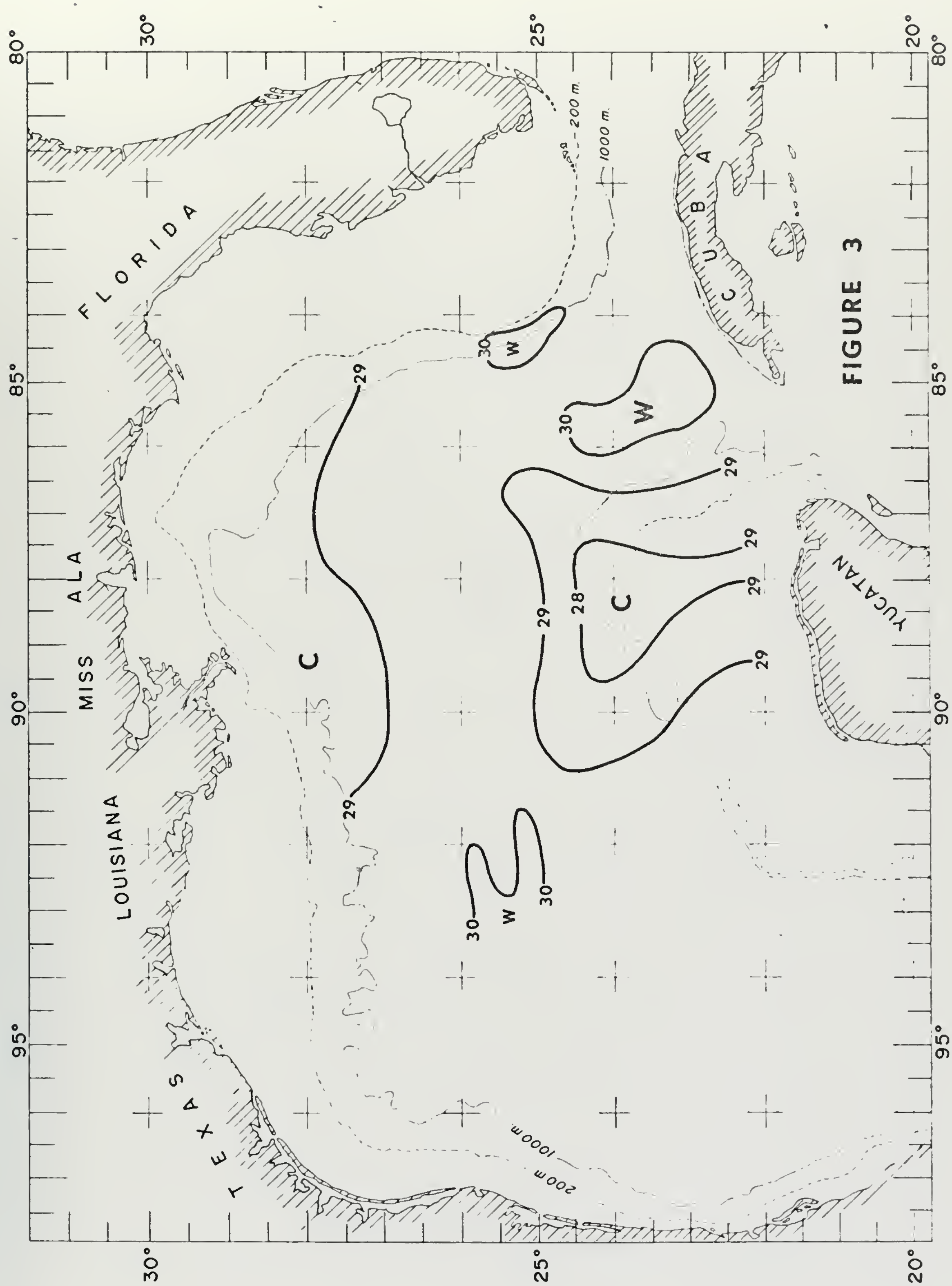


FIGURE 1

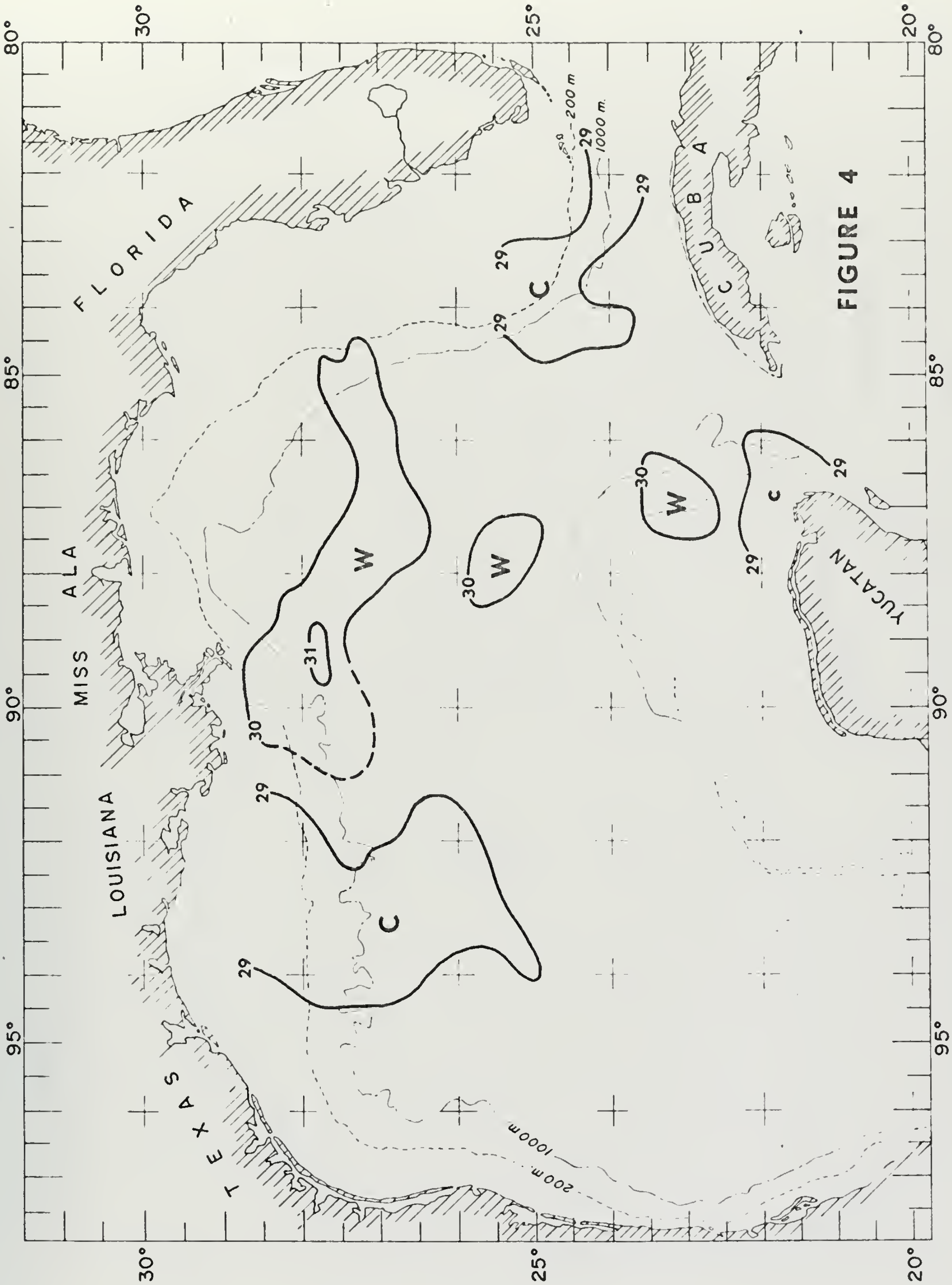
Schematic Comparison of Two Vertical Temperature Distributions



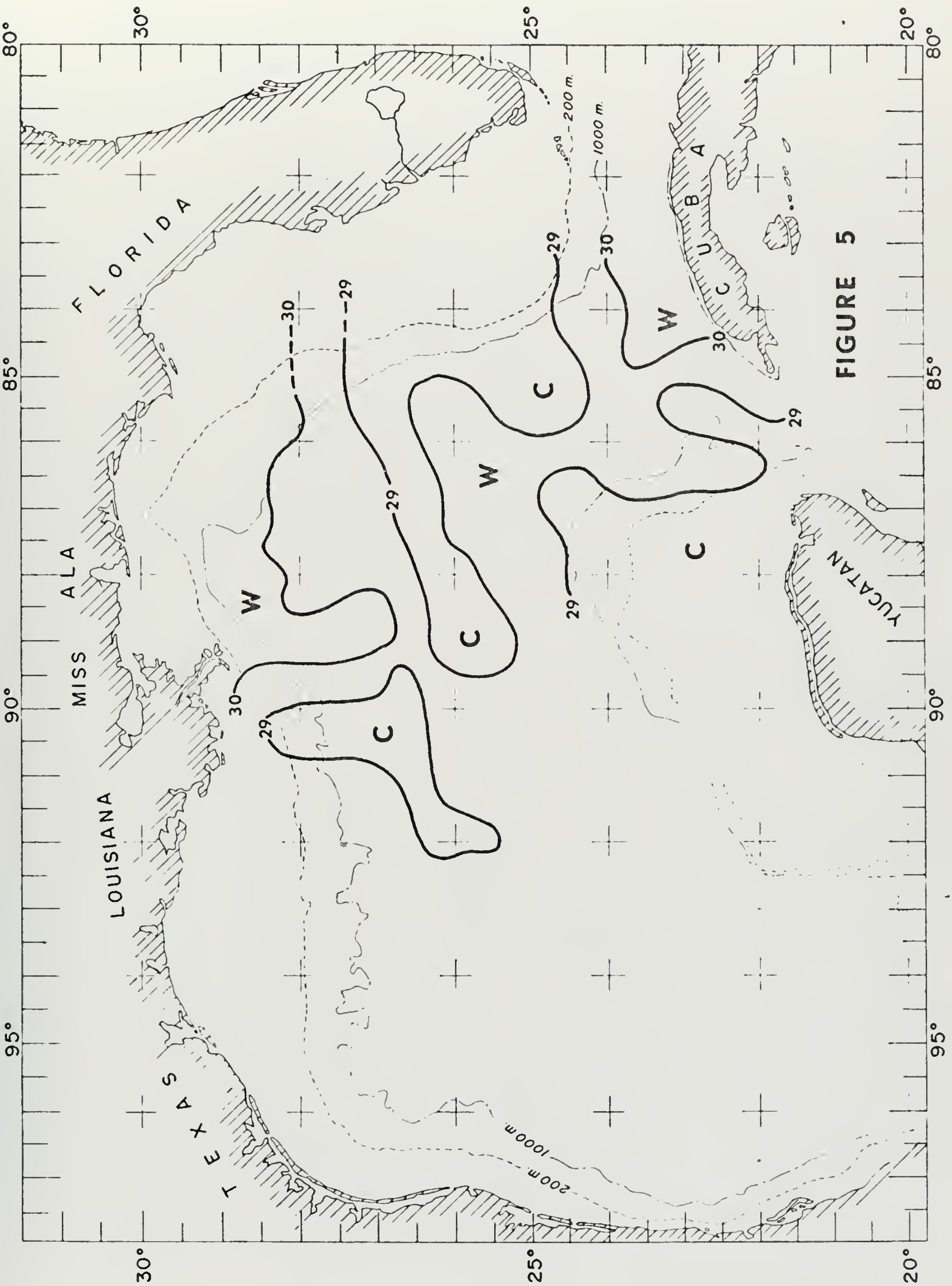
Sea Surface Temperature Analysis for Cruise 65-A-11, 10-24 August 1965 (^{o}C)



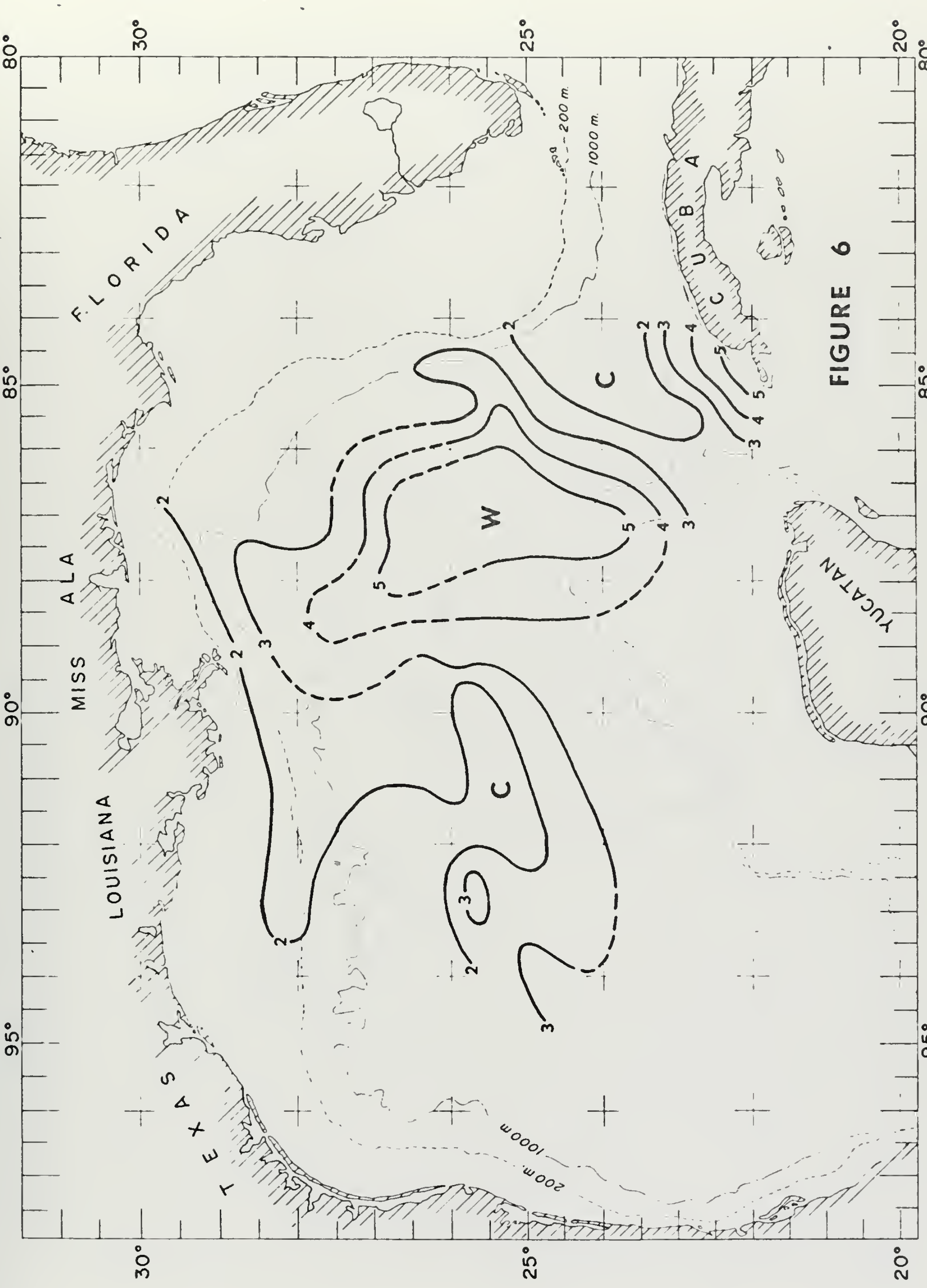
Sea Surface Temperature Analysis for Cruise 66-A-11, 4-18 August 1966 (°C)



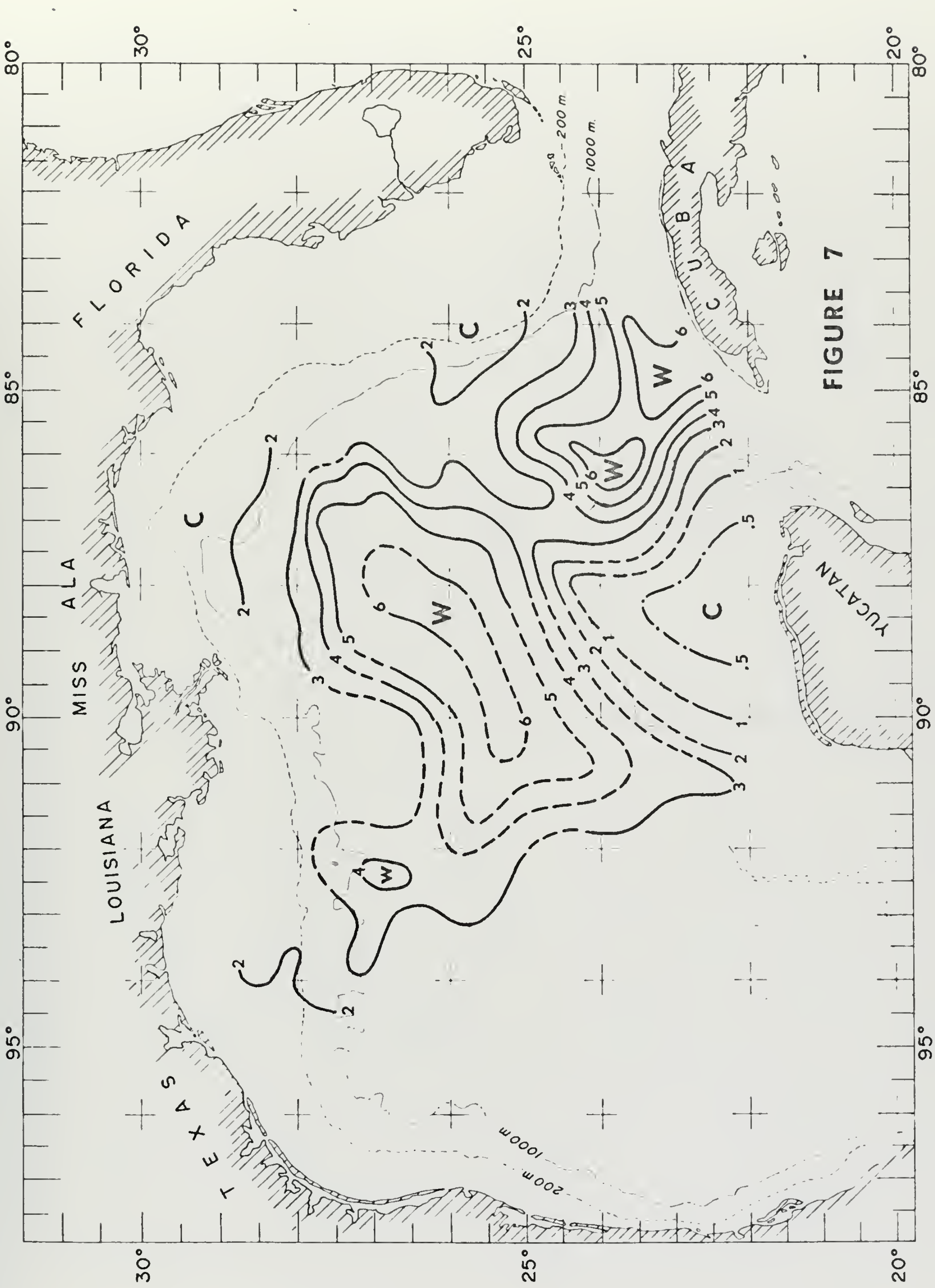
Sea Surface Temperature Analysis for Cruise 67-A-6, 4-22 August 1967 (°C)



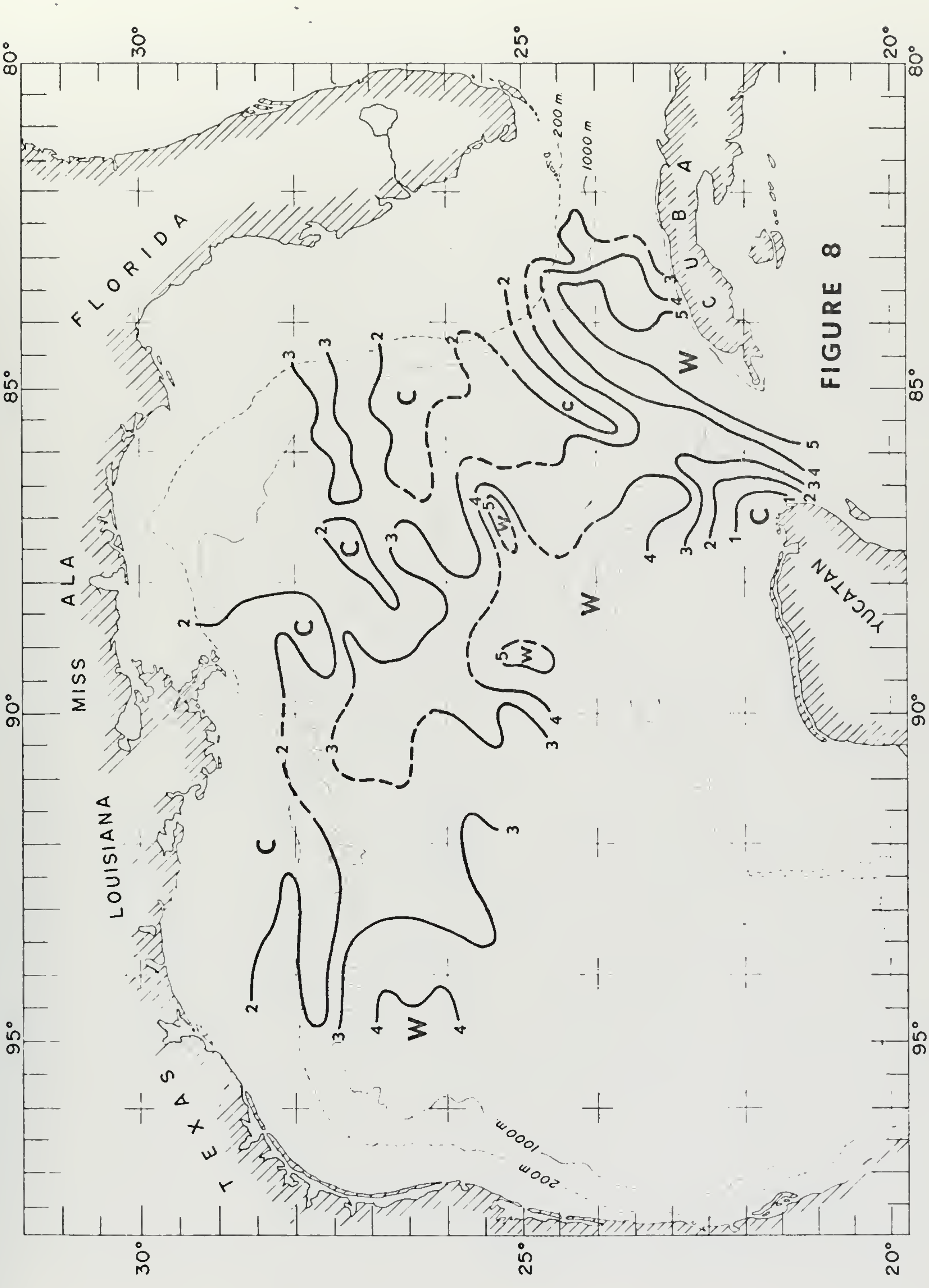
Sea Surface Temperature Analysis for Cruise 68-A-8, 17 August -- 5 September 1968 ($^{\circ}C$)



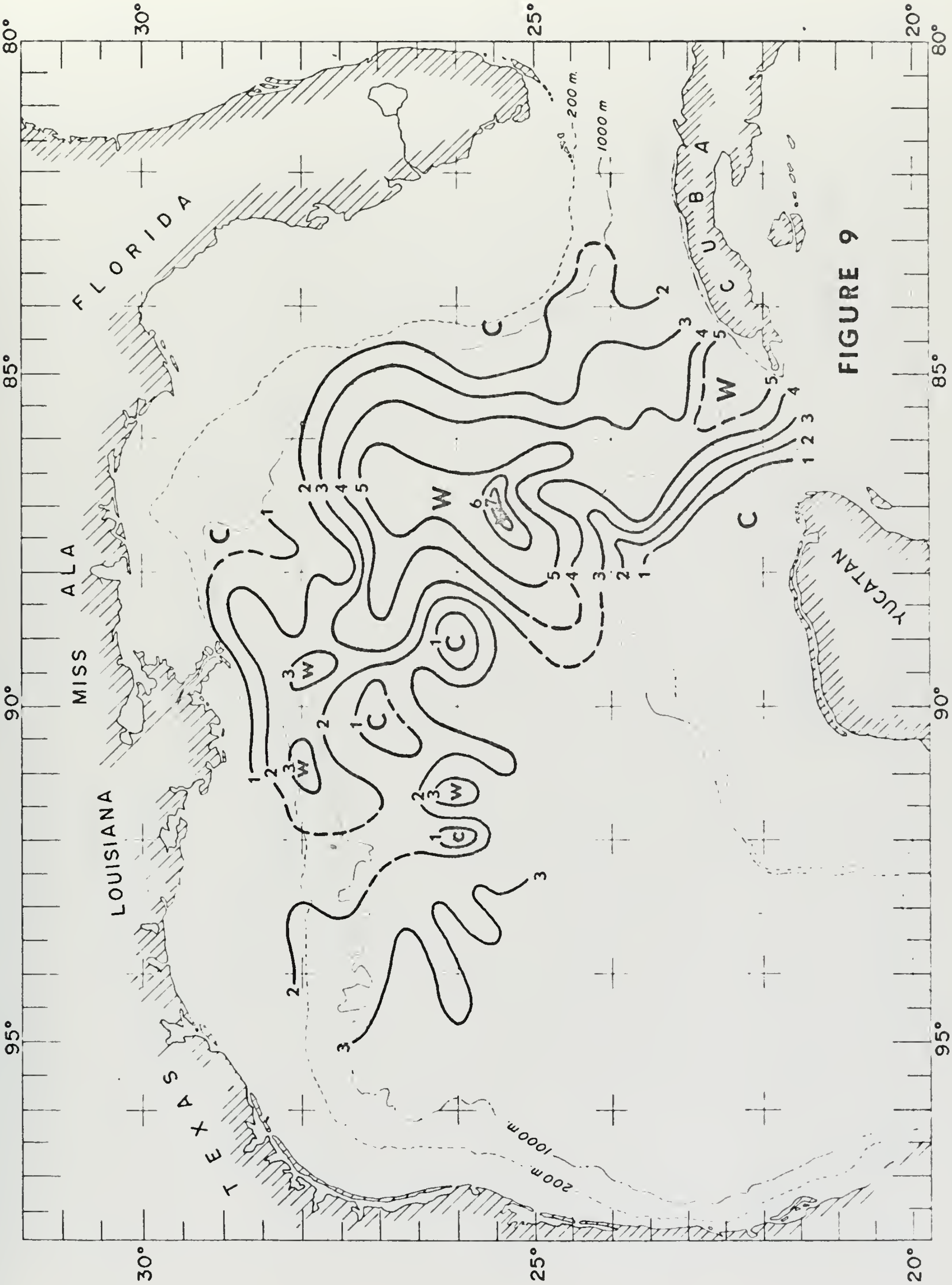
Total Fuel Analysis for Cruise 65-A-11, 10-24 August 1965 (in days)



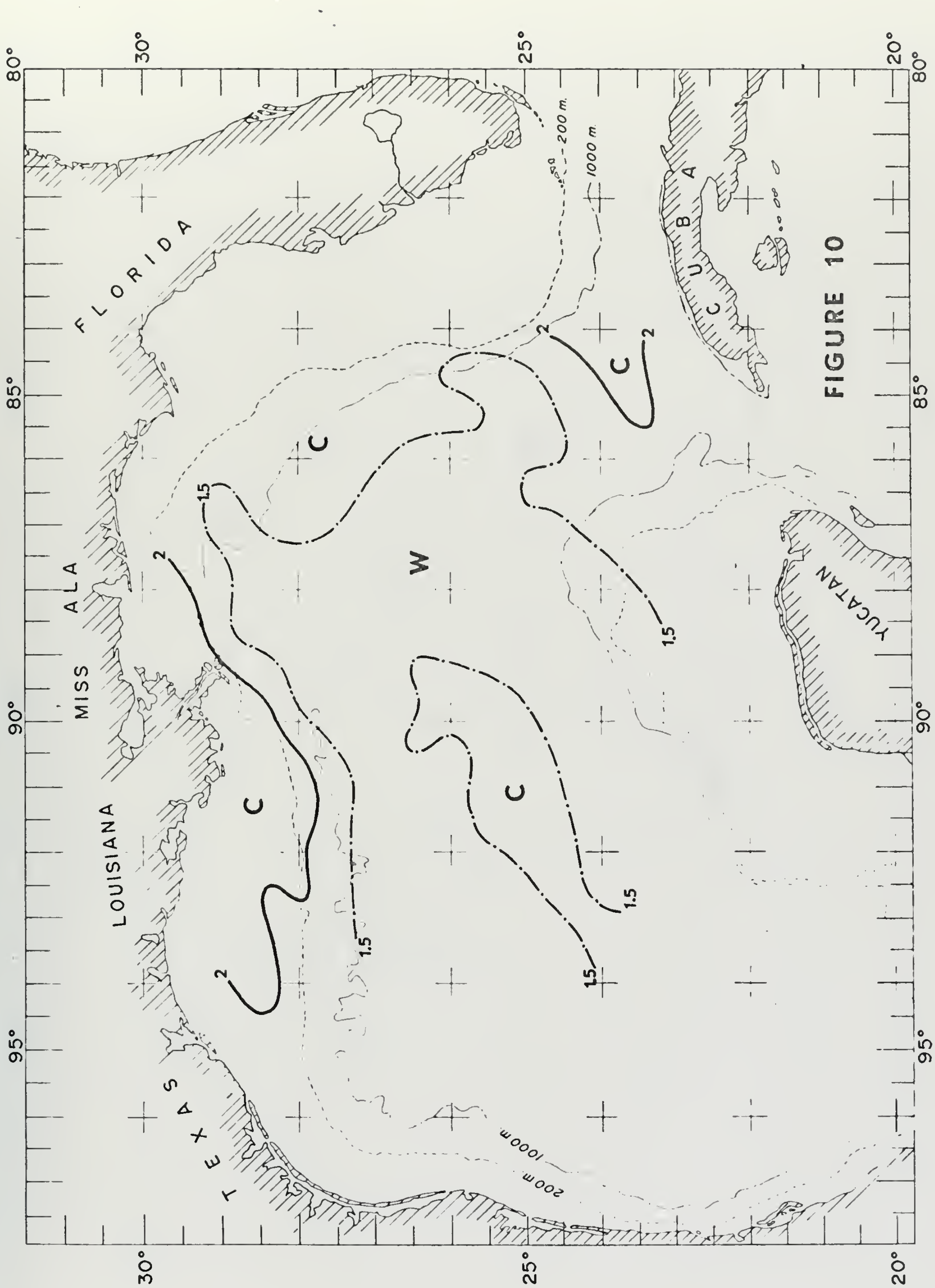
Total Fuel Analysis for Cruise 66-A-11, 4-18 August 1966 (in days)



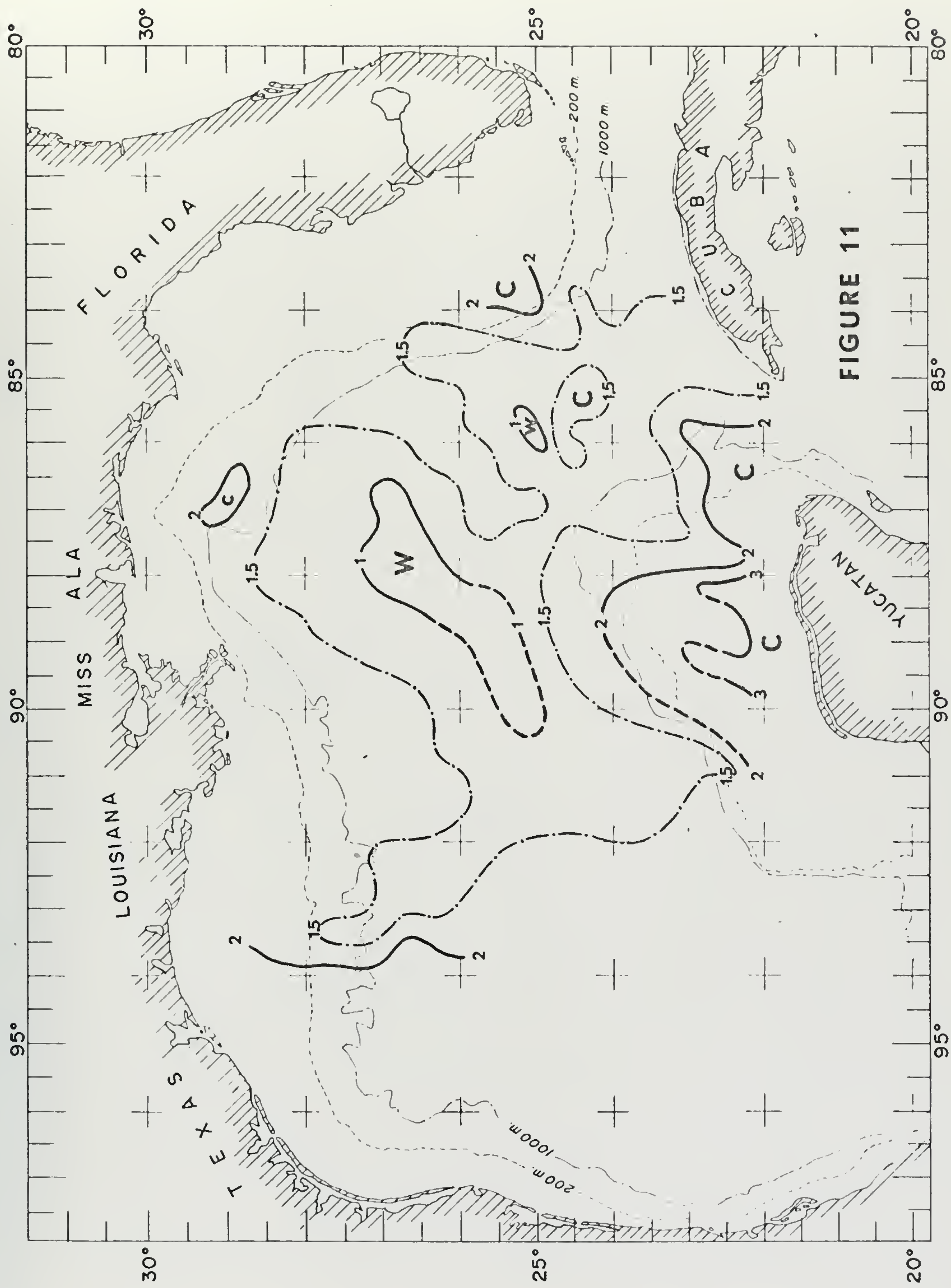
Total Fuel Analysis for Cruise 67-A-6, 4-22 August 1967 (in days)



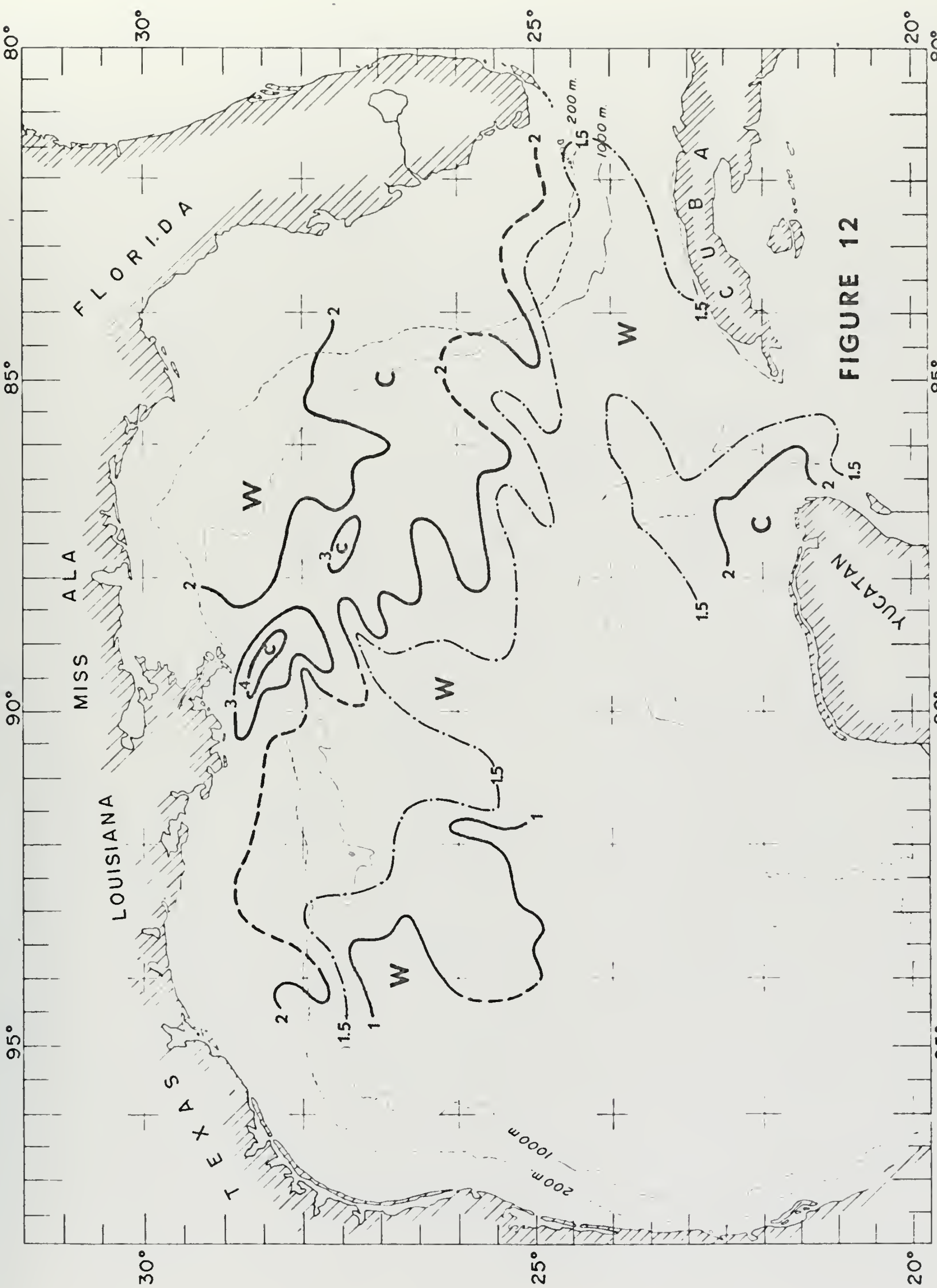
Total Fuel Analysis for Cruise 68-A-8, 17 August-5 September 1968
(in days)



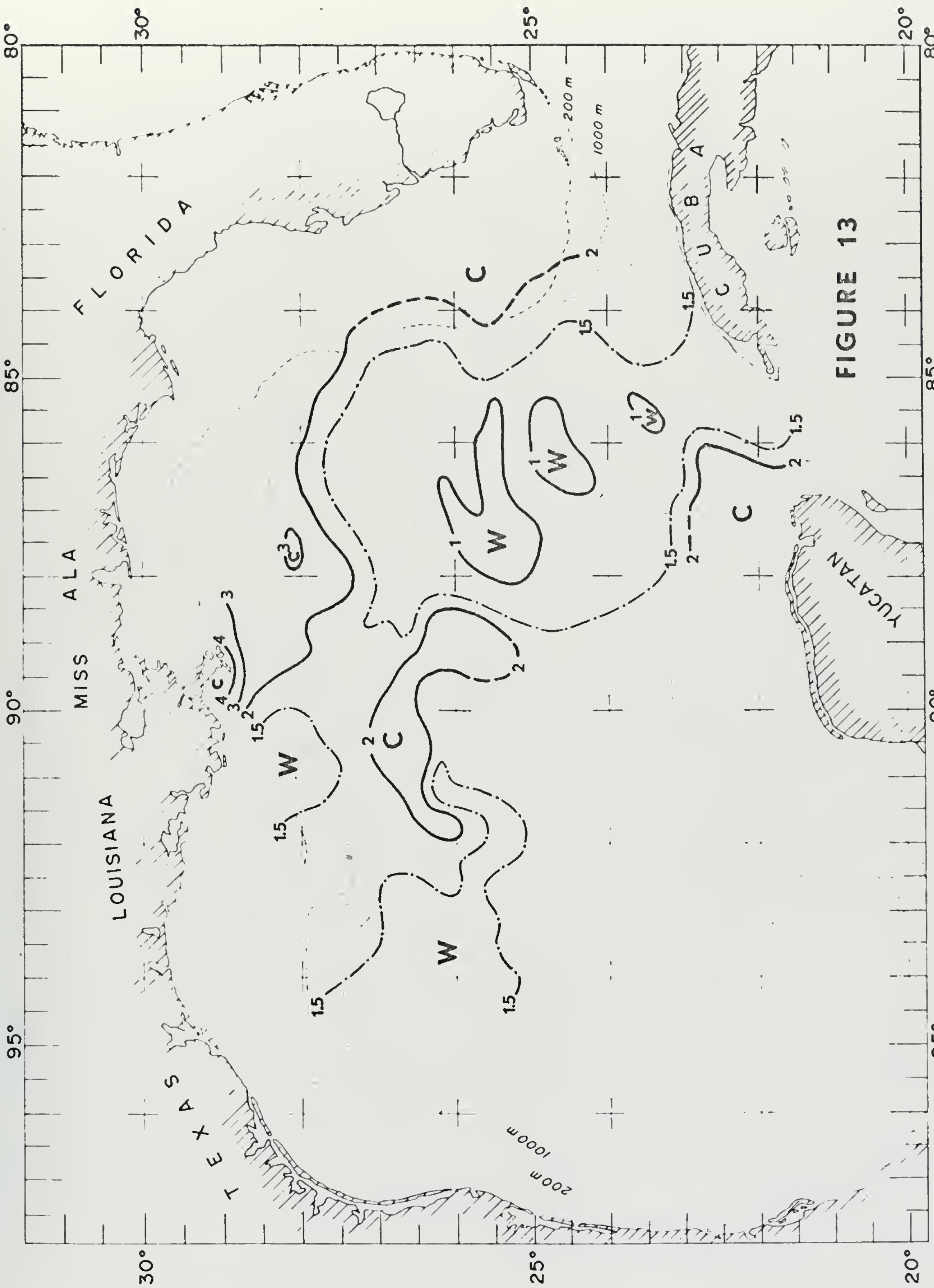
Computed Temperature Decreases Associated with a 24 Hour Hurricane Traverse Time for Cruise 65-A-11, 10-24 August 1965 (^{O}C)



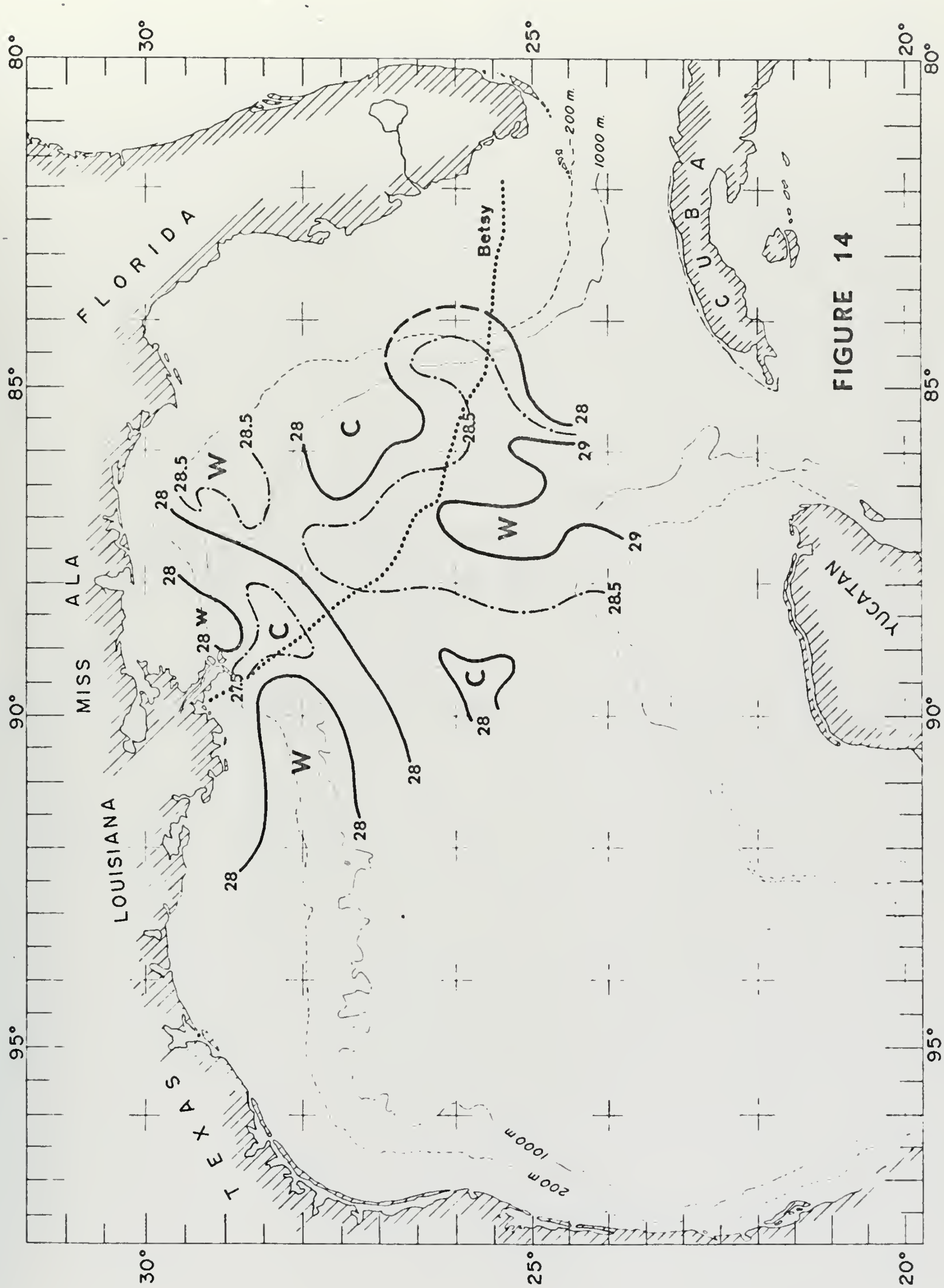
Computed Temperature Decreases Associated with a 24 Hour Hurricane Traverse Time for Cruise 66-A-11, 4-18 August 1966 (^{o}C)



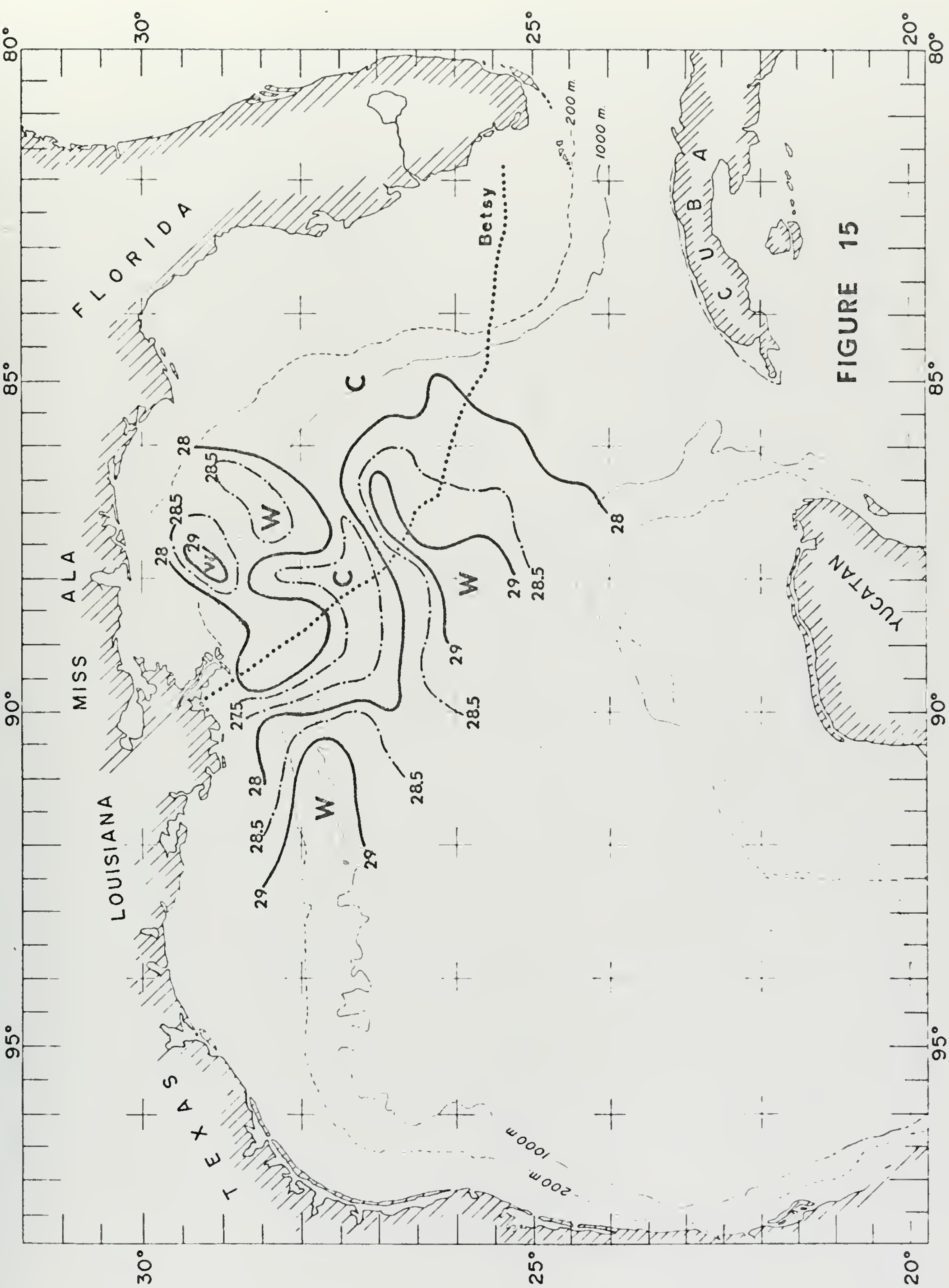
Computed Temperature Decreases Associated with a 24 Hour Hurricane Traverse Time for Cruise 67-A-6, 4-22 August 1967 (^{O}C)



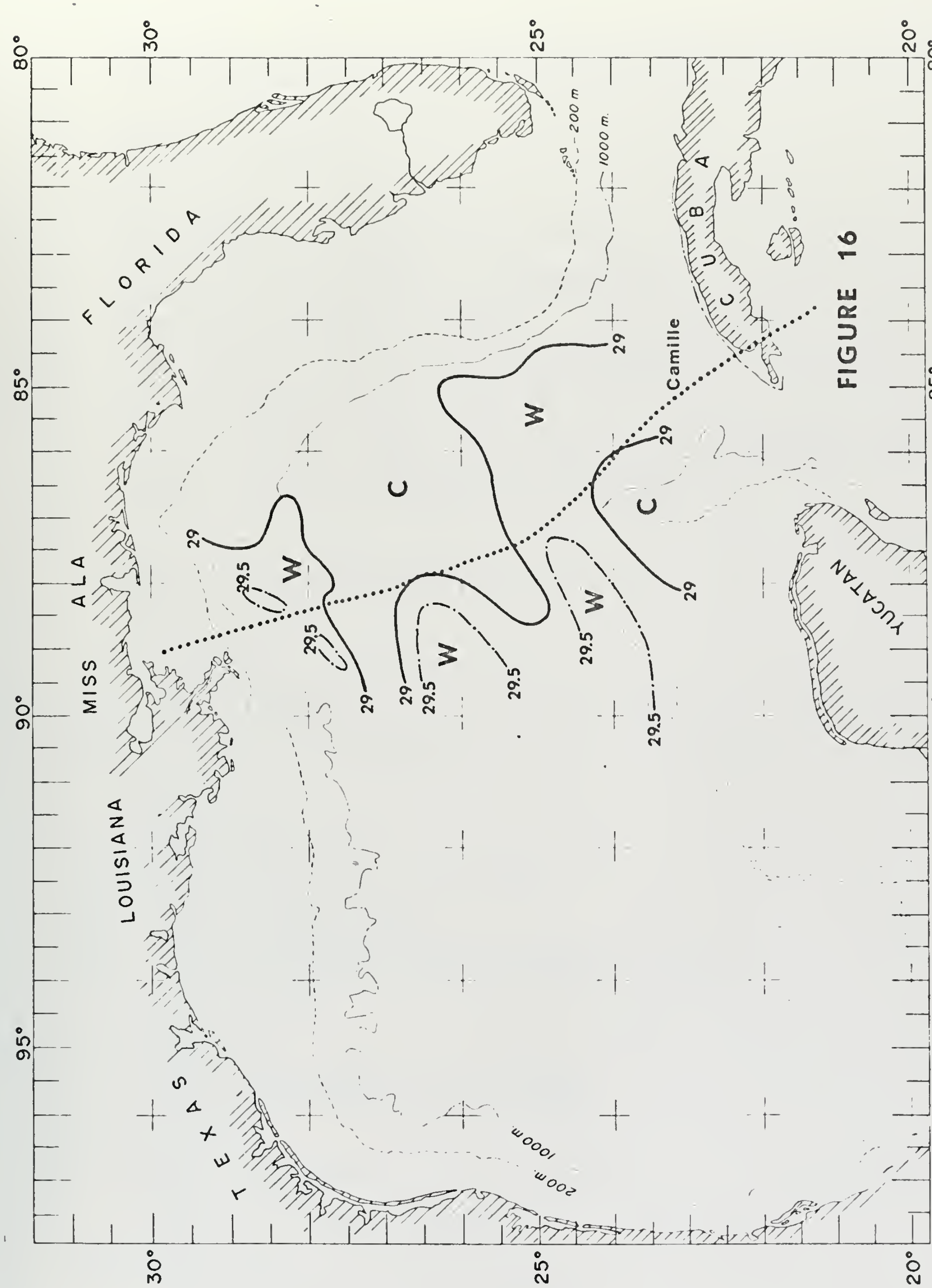
Computed Temperature Decreases Associated with a 24 Hour Hurricane Traverse Time for Cruise 68-A-8, 17 August - 5 September 1968 (^{o}C)



Computed Sea Surface Temperatures Associated with a 12 Hour Hurricane Traverse Time for Hurricane Betsy (1965) (^{O}C)



Observed Sea Surface Temperatures Subsequent to Hurricane Betsy (1965) (^{o}C)



Observed Sea Surface Temperatures Subsequent to Hurricane Camille (1969) (^{o}C)

```
C        THIS PROGRAM REDUCES THE TEMPERATURE OF THE SEA SURFACE
C            TO SIMULATE THE REMOVAL OF HEAT DUE TO THE PASSAGE
C            OF A HURRICANE.
C
C        CRUISE NUMBER.....
C
C      NORMAL PROFILE TECHNIQUE
C
C         N= NUMBER OF STATIONS
C         NP= NUMBER OF POINTS PER STATION
C         NS= STATION NUMBER
C         D(1) OR T(1)= SURFACE TEMPERATURE
C         V= INCREMENTAL TEMPERATURE DROP OF SEA SURFACE TEMP
C         M= DEPTH OF OBSERVATION
C         DUMMY= CONVENIENT TRANSFER STATEMENT ONLY
C         FR= RATE OF TRANSFER COMPARED TO THAT AT ORIGINAL SEA
C             SURFACE TEMPERATURE OF STATION
C         DLT= DIFFERENCE BETWEEN ORIGINAL SEA SFC TEMP AND THE
C             CURRENT SEA SFC TEMP
C         IHRS= TIME IN HOURS TO OBTAIN THAT PARTICULAR SEA SFC
C             TEMP BASED ON REMOVAL OF CLDY CALORIES PER DAY
C         CALR= CALORIES REMOVED PER SIX HOUR INCREMENT
C         CLDY= CALORIES REMOVED PER 24 HOUR DAY
C
C
      DIMENSION ST(30), DLT(30),QT(30),QX(75), X(75), T(75),
     1D(200),NP(500),FR(30)
      N=3
      CLDY= 3500.
      CALR=CLDY/4.
      REF=26.01
      READ(5,100) (NP(I),I=1,N)
  100 FORMAT(40I2)
      WRITE(6,200) N
  200 FORMAT('1',6X,'CRUISE 65 - A - 11, NUMBER OF STATIONS,
     1 ', 5X, 'N =',I5//)
      DO 50 I=1,N
      TOT=0.0
      NN=NP(I)
      READ(5,101) NS
  101 FORMAT(I3)
      READ(5,102) (T(J),J=1,NN)
  102 FORMAT(16F5.1)
      WRITE(6,201) I,NN
  201 FORMAT('0',10X,2I5)
      WRITE(6,202) NS,(T(J),J=1,NN)
  202 FORMAT('0',5X,I3,3X,20F5.1//12X,20F5.1)
      DO 14 J=1,NN
      M=J*5-4
      D(M)=T(J)
   14 CONTINUE
      DO 61 J=6,NN,5
      IF(D(J).GT.D(J-5)) GO TO 997
   61 CONTINUE
      T(1)=D(1)
      V=.1
      DO 53 L=2,100
      T(L)=T(1)-V
      V=V+.1
      IF(T(L).LE.REF)GO TO 716
   53 CONTINUE
  716 X(1)=0.0
      IF(D(6).EQ.D(1)) X(1)=500.
      IF(D(11).EQ.D(1)) X(1)=1000.
      IF(D(16).EQ.D(1)) X(1)=1500.
      IF(D(21).EQ.D(1)) X(1)=2000.
      IF(D(26).EQ.D(1)) X(1)=2500.
      IF(D(31).EQ.D(1)) GO TO 999
      M=2
      NX=NN*5-4
      DO 55 L=6,NX,5
      K=L-5
```

```
      DOOR=D(L)-.01
   77 IF(T(M).LT.DOOR)GO TO 55
      ADD=(500.*(D(K)-T(M))/(D(K)-D(L)))
      VAL=K-1
      J=M-1
      X(M)=VAL/5.*500.+ADD
      IF(M.EQ.2) GO TO 40
      ATT=(500.*(D(K)-T(M-1))/(D(K)-D(L)))
      X(M-1)=VAL/5.*500.+ATT
   40 QX(J)=((X(M)+X(M-1))/2.)*.1
      TOT=TOT+QX(J)
      IF(T(M).LE.REF)GO TO 715
      M=M+1
      GO TO 77
   55 CONTINUE
  715 DUMMY=23.
      WRITE(6,213) TOT
  213 FORMAT('OTOTAL HEAT EXCHANGED = ',F10.1,' CALORIES.')
      WRITE(6,207)
  207 FORMAT('0',5X,'HOURS',7X,'SST',6X,'DELTA SST',4X,'TRAN
     1SFER RATE',8X,'SUM')
      LO=1
      QT(1)=0.0
      SUM=0.0
      DO 57 IS=1,100
      QTY=CALR*(IS-1)+900.
   93 SUM=SUM+QX(LO)
      IF(SUM.GE.QTY)GO TO 98
      LO=LO+1
      IF(LO.EQ.M)GO TO 50
      GO TO 93
   98 SO=LO
      ST(IS)=D(1)-.1*SO
      DLT(IS)=D(1)-ST(IS)
      FR(IS)=1.-(DLT(IS)/(D(1)-26.))
      IHRS=IS*6
      WRITE(6,208) IHRS,ST(IS),DLT(IS),FR(IS),SUM
  208 FORMAT(' ',7X,I3,6X,F4.1,11X,F4.1,10X,F7.3,3X,F9.1)
      LO=LO+1
      IF(LO.EQ.M)GO TO 50
   57 CONTINUE
      GO TO 50
  997 WRITE(6,210) NS
  210 FORMAT('OSTATION NUMBER ',I3,' HAS AN INVERSION.')
      GO TO 50
  999 WRITE(6,209) NS
  209 FORMAT('OSTATION NUMBER ',I3,' HAS A COMPUTATIONAL ANA
   50 CONTINUE
  720 STOP
      END
C
C     SAMPLE DATA CARDS WHICH REFER TO THE FIRST THREE STATIO
C          NS TO BE ANALYZED ARE AS FOLLOWS...
C
050709...ETC....
001
0 297  295  290  283  259
002
0 293  293  289  280  276  272  260
003
0 301  300  298  297  289  285  276  272  258
C...ETC....
```

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13. ABSTRACT

Analyses were made of the sea surface temperatures in the Gulf of Mexico in August for the four years 1965 through 1968. No one pattern was found to predominate. The subsurface temperature profiles were then considered, and a rate of simulated withdrawal of 4000 calories of heat per day was made, until there was no heat in excess of 26°C. This withdrawal represented heat removed during passage of a hurricane. Difference analyses were constructed for the initial sea surface temperature at each station and that after twenty-four hours of simulated withdrawal. The differences ranged from less than one degree to over four degrees. Again, no consistent pattern was found but generally areas of high concentrations of heat experienced smaller decreases. Actual sea surface temperatures collected after two hurricanes were then analyzed and compared to temperature patterns predicted by the computer model. Illustrations of the relative availability of sensible heat energy for different sea surface temperatures are presented and a hypothesis made to account for the greater than average intensities of Hurricane Betsy (1965) and Camille (1969).

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